Int J Life Cycle Assess (2014) 19:272–284
DOI 10.1007/s11367-013-0639-4

BUILDING COMPONENTS AND BUILDINGS

LCA case study. Part 2: environmental footprint and carbon tax of cradle-to-gate for composite and stainless steel I-beams

Suphunnika Ibbotson · Sami Kara

Received: 1 June 2012 / Accepted: 4 August 2013 / Published online: 5 September 2013

Abstract

Purpose Part 1 of this research investigated environmental footprint for the cradle-to-grave of a linear metre I-beam made from traditional and alternative materials which are stainless steel (316) and glass reinforced plastics (GRP). Results revealed that GRP generally produced less environmental footprint than stainless steel. The main contribution found in the cradle-to-gate caused by raw materials (90 %) and associated transportation (10 %). Certain impact categories of GRP were either equalled or higher than stainless steel I-beam including the climate change impact category. Therefore, part 2 of this research further investigates the ecological and economic hot spots of the cradle-to-gate of GRP I-beam and alternative supply chain scenarios. The potential carbon tax was also estimated under two different situations.

Methods GRP and stainless steel (316) are used to assess the environmental footprint and the economic impact of 6,098 m I-beams as a production volume in practice. The World ReCiPe midpoint and endpoint methods generated the life cycle inventory, characteristic and single score results for the environmental footprint. The economic impact estimated based on a simple cost calculation associated with the cradle-to-gate including material, production and transportation costs. The ecological and economic hot spots were identified and formed 12 supply chain scenarios.

Results and discussion Both identified hot spots came from raw materials that used in large quantities, consumed higher electricity and delivered by road and water transportation over long travel distances. The climate change impact category and the potential carbon tax values are improved under the scenarios that use a supplier from countries that generate electricity from less coal-based energy source and involve less transportation in delivering the raw materials.

Conclusions Win–win and trade-off scenarios were revealed when comparing both impacts. The former scenario reduces material costs, the travel distances and using lower freight rate transportation that consumes less fuel such as shipping. The latter scenarios are often occurred by either attempting to reduce the environmental footprint from using less transportation but the raw material costs are suffered. Manufacturers may select the scenario based on their production constrains. Cradle-to-grave was discussed and shown the benefits in including steel recycling into the assessment which can equate the potential carbon tax of the stainless steel with some GRP I-beam scenarios. Future work can be enhanced by considering other factors in the practice of manufacturing system such as insurance cost and lead time.

Keywords Carbon tax · Cradle-to-gate · Economic impact · Environmental footprint

Abbreviations

NH_3	Ammonia
CO_2	Carbon dioxide
CO_{2eq}	Carbon dioxide equivalent
CPI	Consumer price index
GRP	Glass reinforced plastics
GHG	Greenhouse gas
HDPE	High density polyethylene
LCIA	Life cycle impact assessment
LCI	Life cycle inventory
SO_2	Sulphur dioxide
t	Tonne

Responsible editor: Holger Wallbaum

S. Ibbotson (✉) · S. Kara
Sustainable Manufacturing & Life Cycle Engineering Research Group, School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia
e-mail: suphunnika@unsw.edu.au

S. Ibbotson
e-mail: suphunnika@yahoo.com

1 Introduction

Building construction plays a significant role in our societies as it provides many services for numerous essential infrastructures. Designing a building construction is considerably complex. It has to satisfy the legal safety requirements and the financial constraints of the investors (Lee et al. 2006; Bakis et al. 2002). The construction integrity must be fulfilled while sustaining the construction cost within the restricted budget. Basic construction costs often consider material, transport, installation, labour and maintenance costs (Agrawal and Tiwari 2010; Tae et al. 2011). Naturally, these costs are varied over time due to the influences of the domestic and world commodity prices, and inflation rate.

Nowadays, the building constructions are not only pressured by those legal and economic pressures but also by certain government regulations that require them to improve their environmental performance (Helm 2005; Woodard 2011). Amongst the legislations, carbon tax emerged since 2005 (Sumner et al. 2009) to satisfy the Kyoto protocol (United Nations 1998) and is critical. This tax scheme is predicted to have a significant impact in broader global and local economy. Economically, the carbon tax scheme will have an impact on the construction costs due to the rising commodities prices from their raw materials such as steel and concrete (Metz et al. 2007; Sumner et al. 2009). Australia government enforced the carbon tax bill which is enacted since July 2012 where the emission trading scheme will subsequently be established later in 2015 (Australian Government 2013). This carbon tax price is 23 Australian dollars (AU$(2011) per tonne of carbon emissions (tCO_2) which is initially implemented to the big polluters who emit over 25,000 tonnes (t) per year (Australian Government 2013). Although, the current tax is excluding the emissions caused by the heavy transportation, it is expected to be included in the future.

Much research has investigated the environmental footprint and economic impact for different material types in various applications (Agrawal and Tiwari 2010; Ashby 2009; Dlamini et al. 2011; Dobon et al. 2011; Hochschorner and Noring 2011; James 2003; Kara et al. 2010; Kicherer et al. 2007; Lee et al. 2006; Rainer 2011; Schulz et al. 2011; Tae et al. 2011; Tsai et al. 2011; Laurent et al. 2010; Lévová and Hauschild 2011; Song et al. 2009). In principle, environmental footprint or environmental impact influences human health, ecosystem quality and resource scarcity which are caused by the resource consumptions, wastes and emissions that are produced by those various applications. Economic impact is theoretically associated with different direct and indirect costs and benefits that are generated by the applications.

For instance, Dlamini et al. (2011) analysed life cycle assessment (LCA) of steel and HDPE car fuel tanks. They found that steel tank has high impact in the mineral category while High density polyethylene (HDPE) has high contribution in the fossil fuel. HDPE has relatively less environmental impact than the steel; however, the environmental performance of steel is increased when considering recycling process after the 62-year life span. Tae et al. (2011) compared life cycle carbon dioxide (CO_2) and building cost for four different apartment buildings built with plaster board drywall scenarios which consider the construction, operation and maintenance, demolition and waste stages, including the transportation involved. Hong et al. (2007) simulated optimal life cycle costing (LCC) for the fibre reinforced polymer (FRP) composite bridge deck panels and James (2003) assessed the environmental LCC of food packaging supply chain in Australia.

A number of studies also focus on both LCA and LCC (Kara et al. 2007; Witik et al. 2011; Castella et al. 2009). Castella et al. (2009) compared LCC and environmental impacts of the composite and steel rail car-bodied. Both impacts of the composite rail were found to be less than the steel rail by up to 16 % and 26 %, respectively. Witik et al. (2011) assessed LCC and environmental performance for the lightweight materials in automobile applications. Lighter weight vehicle such as sheet moulding compounds like composites was found to perform better in an overall even though it cannot be recycled. This is due to the cost reduction of the fuel consumption during the usage stage. Kara et al. (2007) developed an integrated tool to assess simplified LCA and associated social cost which applied in various consumer products.

Part 1 of this research have investigated the environmental footprint for the cradle-to-grave of 1 m I-beam made from the traditional and alternative materials which are stainless steel (316) and glass reinforced plastics (GRP; Ibbotson and Kara 2013). The system boundaries of the products were based on the raw materials, emissions and wastes involved with the raw material extraction, transportation associated with sourcing materials, manufacturing process, distribution and disposal transportation as well as disposal process.

On this occasion, stainless steel was selected as the traditional material to compare with GRP to highlight the application of the I-beam in the marine environment where corrosion is the main concern. Stainless steel I-beam was produced in Australia by 60 % of primary material and 40 % secondary material, transported by road transportation to a manufacturing plant and hot rolling to form I-beam. It was assumed as 70 % recycling and 30 % incineration processes. GRP I-beam is sourced and transported raw materials from different suppliers to the manufacturing plant in Australia, manufactured using pultrusion process and assumed 100 % incineration. Due to the marine environment, the life time of both products was assumed to be the same based on their warranty conditions; therefore, no maintenance activities were included (Ibbotson and Kara 2013).

The single score results from the World ReCiPe endpoint method revealed that GRP I-beam is generally produced 20 %

less environmental footprint than stainless steel I-beam. The differences of the results were owing to the high contribution from the cradle-to-gate of the I-beams which largely contributed by the material stage up to 90 %. This stage considers raw material extraction process and the associated transportation from suppliers to the manufacturing plant. Moreover, an interesting finding was identified that the GRP I-beam has higher proportion of the environmental footprint caused by the associated transportation (up to 10 %) than that of the stainless steel I-beam. The transportation was extensively used to move the raw materials from the suppliers to the manufacturing plant. However, the opposite was true when observing the characteristic results from the World ReCiPe midpoint method. Most impact categories of GRP I-beam performed better than the stainless steel I-beam except certain impact categories of GRP I-beam which were either higher or equal to the stainless steel product. These impact categories were the climate change, ozone depletion, photochemical oxidant formation, terrestrial acidification, marine eutrophication, natural land transformation and fossil depletion.

Due to the findings and such drawbacks of these results of GRP I-beam which caused by supply chain parameters during its cradle-to-gate, further investigation is performed in this research to demonstrate the possible improvements in altering supply chain situations. However in practice, such situations must not only propose better environmental performance options to manufacturers but also cost effective options to maintain their competitiveness. Therefore, part 2 of this research aims to demonstrate both ecological and economic impacts of the two I-beam products. The ecological impact is a continuation of part 1 which had covered the assessment of the cradle-to-grave for 1 m I-beam; hence, those two World ReCiPe methods were used to observe the variations of the single score results and the characteristic results for the cradle-to-gate of 6,098 m for the two products. The specific length of the I-beams significantly represents the production and its impact in practice. The single score results represent the total environmental footprint that relates to human health, ecosystem quality and resource use. Amount of CO_2 and greenhouse gases (GHG) was also obtained to highlight their influences towards the climate change and to use in estimating the possible carbon tax for the economic impact. The economic impact of the products was also estimated by focusing on the direct production cost which mainly includes material, transportation and process costs. Results from both assessments were used to identify hot spots and formulate 12 supply chain scenarios. Subsequently, the ecological and economic impacts of the cradle-to-gate were analysed for the current and the formulated scenarios of the 6,098 m products to demonstrate the production in practice. Finally, the economic impact is further analysed for two different market price situations which are: (a) the current Australian carbon tax situation where the carbon tax accounts for CO_2 emission and (b) the Kyoto protocol situation where GHG emissions.

2 Methodology

2.1 Methodology overview

In brief, this research aims to estimate the environmental footprint and cost associated with the current of the cradle-to-gate for 6,098 m of GRP I-beam to identify the ecological and economic hot spots which were then used to formulate 12 different supply chain scenarios. This is to demonstrate the current production's practice situation. Furthermore, the economic impact was investigated further for the potential carbon tax values and the total market prices under two different market price situations of both GRP and stainless steel products. They are:

(1) The current Australian carbon tax which accounts only emitted CO_2 during the cradle-to-gate including the emissions from the heavy transportation and
(2) The Kyoto protocol which considers GHG emissions during the cradle-to-gate.

The aforementioned assessments were based on the assumptions in the following subsections.

2.2 Environmental footprint assessment

The functional unit of the environmental footprint assessment is the cradle-to-gate of 6,098 m of GRP and the stainless steel I-beams cover activities from the raw material extraction, materials processing and transportation from suppliers to the manufacturer until manufacturing processes transformed the raw materials into I-beams. Therefore, the analysis was based on 6,098 m of the I-beams that equal to the production of 20,000 t of GRP I-beams and 23,963 t of the stainless steel I-beams. The length of the I-beams was based on the production volume of GRP I-beam.

The environmental footprint assessments were conducted based on the life cycle inventory (LCI) databases namely the Ecoinvent 2.2 (Ecoinvent Centre 2010) and the Australian data 2007 (PRe Consultants BV 2008) and the life cycle impact assessment (LCIA) method called the World ReCiPe midpoint and endpoint methods (Goedkoop et al. 2009). Full assumptions and modifications of the assessments can be observed in part 1 (Ibbotson and Kara 2013). A summary of LCI is provided in Table 1. The main modifications were made for the process cases of these LCI databases to accommodate the missing electricity mix processes of the five associated countries of the suppliers. The modified electricity

Table 1 Summary of the Life Cycle Inventory for the cradle-to-gate of 6,098 m composite and the stainless steel I-beams

Life cycle stages	Activities	Composites (SCQ)	Stainless steel (SS)
Material	Raw material extraction	20,000 t of 14 raw materials from 5 different countries (Australia, the USA and 3 Asian countries)	23,963 t of stainless steel (316): 60 % primary and 40 % secondary materials
	Transportation from suppliers to the manufacturing plant	Trucks and ships	A truck (1,000 km)
Manufacturing process	Process	Pultrusion	Hot rolling

process cases were used for the raw material extraction, materials processing and the manufacturing processes. The cases were modified by altering the amount of energy resources of the Chinese electricity mix process case to match with the amount of the five countries reported in International Energy Agency (IEA) in 2008 (International Energy Agency 2008). These energy resources included coal, oil, gas, biomass, waste, nuclear, hydropower, geothermal, solar, wind and other resources. The validation was made by comparing the amount of CO_2 per kWh of the modified process cases with the value reported in IEA's CO_2 emission reports (International Energy Agency 2009; International Energy Agency 2010; International Energy Agency 2011).

The impact assessment was performed to produce the environmental footprint results in terms of carbon emission (kg CO_2 of fossil fuels), GHG emissions (kg CO_{2eq}), the characteristic (in various units) and the single score (points) results. These results were extracted from the results from LCI, the climate change category and the characteristic results of the World ReCiPe midpoint method, as well as the weighted World ReCiPe endpoint methods respectively. The single score results are the aggregation of 17 impact categories such as the climate change human health, the ozone depletion and human toxicity which are presented in the results section (see Fig. 3).

2.3 Economic impact assessment

The economic impact was assessed based on the same functional unit as the environmental impact assessments, which is the cradle-to-gate of 6,098 m I-beams. The cradle-to-gate included different raw material costs, associated transportation costs for moving raw materials to the manufacturing plant and the overhead cost. These costs were estimated based on the company data and the market price values found in extensive literatures and commercial advertisement on the public domain information (Patrawala 1999; Bureau of Labor Statistics 2011; PULTRUSIONS.org 2012; Rate Inflation 2011; Risbey et al. 2008; Starr 2000; United Business Media 2012; X-RatesTM 2012; Tuakta 2004; Goel 2000; Daniel 2003; Orozco 1999; Wittcoff et al. 2012). The assessment converted the collected price data into Australian dollar value in 2011, AU$ (2011) using the exchange rate (X-Rates™ 2012) and (CPI; Rate Inflation 2011) as given in Eq. 1.

$$2011AUD\$ = \left[US(2009) \times \left(\frac{1.0AUD\$(2009)}{0.8US\$(2009)}\right)_{Exchange\ rate}\right] \times \left(\frac{2011AUD}{2009AUD}\right)_{CPI} \qquad (1)$$

On this occasion, the estimation for the total market price of the 6,098 m GRP I-beam was mainly based on the total market price which was assumed to include 50 % of production cost and another 50 % of profit and tax (Marsh 2000). The assumed production cost includes 85 % of material cost and 15 % of overhead cost (Marsh 2000; PULTRUSIONS.org 2012).

Further assumptions are described as follows:

Materials The 85 % material cost is consisted of 76 % of raw material cost and 9 % of transportation cost. The raw material cost was the summation of 14 raw material prices found on the online advertisement from suppliers in five different countries (Australia (AU), ASIA1, ASIA2, ASIA3 and the USA). These market prices have a standard deviation of 2.71 AU$(2011) and the coefficient of variation of 109 % due to the differences in the main ingredient such as plastic resins and some chemicals.

Transportation The transportation cost for the travel distances of moving raw materials from suppliers to the manufacturing plant was based on a tonne kilometre (tkm), which is the multiplication of the travel distances in kilometre (km) and the carriage weight in *t*, and the Australian freight rate for water, rail, road transports. The rates are 0.03, 0.04 and 0.08 AU$ (2011) per tkm, respectively (Risbey et al. 2008).

Manufacturing process The 15 % overhead cost was assumed as the sum of electricity, labour, machine and administration costs that spent during the manufacturing process (Starr 2000). The electricity cost was estimated from the manufacturer's estimated electricity consumption and Australian electricity price. The assumed labour cost was the multiplication of Australian labour rate (Bureau of Labor Statistics 2011) and

the estimated operating hours for the 6,098 m I-beams (Kara and Manmek 2010). The remaining costs of the overhead cost were subsequently allocated to machine and administration costs.

Potential carbon tax from those CO_2 and CO_{2eq} emissions The potential carbon tax values were estimated based on 23 AU$ (2011) per tCO_2 (Australian Government 2013) by multiplying with the amount of CO_2 and CO_{2eq} emissions generated from the environmental footprint results.

In addition to this, the value of the stainless steel 316 price was found in many literatures which often indicate higher price than the composite product (Bakis et al. 2002). Therefore, this research assumed for a material cost of a construction made of stainless steel to be 10 % higher cost than that of the GRP (Plsek and Stepanek 2010; Daniel 2003).

2.4 Hot spot analysis and supply chain formulation

Once the environmental footprint and economic impact for the cradle-to-gate of the current GRP I-beam were assessed on the basis of those prescribed assumptions, their hot spots were identified by observing the raw materials and associated transports that contributed highly in both impacts. The identified hot spots were then used to formulate 12 different supply chain scenarios. These scenarios were developed to improve the hot spots as well as demonstrate the influences of different supply chain parameters. In this research, the focused parameters involved travel distances, transportation types and the locations of suppliers. These variables directly associate with the environmental footprint and economic impacts due to their variations determine the fuel consumption of the alternative supply chain scenarios. Moreover, the locations of suppliers also affect different combination of energy resources of the electricity used in different countries as well as the material costs.

The hot spots were found in particular raw materials, M in the material stage of the current or status quo composite I-beam (SCQ) as highlighted in Table 2 (shaded section). The hot spots of M3, M4, M8, M9 and M14 are identified based on the hot spot results provided in section 3.1. The material stage includes raw material extraction, materials processing and transportation used from suppliers to the manufacturing plant. As a result, 12 different supply chain scenarios (SC), SC1 to

Table 2 Input data for the cradle-to-grave of the I-beams

Supply chain scenario	Supplier location	Distance (km) from suppliers to the manufacturer	Type of transport
Inputs of the status quo (SCQ)			
M1	ASIA1	11,000→40	RD→W→RD
M2, M5, M6, and M13	AU	Ranged from 150 to 1,200	RD
M3	AU	1,500	RD
M4, M7, and M8	USA	4,500→18,000→40	RD→W→RD
M9	ASIA1	1,000→11,000→40	RD→W→RD
M10, M11 to M12	ASIA3	8,500→40	W→RD
M14	ASIA2	500→15,000→150→40	RD→W→RD→RD
Supply chain scenarios for improving the identified hot spots			
SC 1	M3	M3: 1,500	M3: RL
SC 2	M3	M3: 150	M3: RD
SC 3	M4 and M8	M4 and M8: 4,500→18,000→40	M4 and M8: RL→W→RD
SC 4-1	M3: ASIA1	M3: 11,000→40	M3: W→RD
SC 4-2	M3: ASIA2	M3: 500→15,000→150→40	M3: RD→W→RD→RD
SC 4-3	M3: ASIA3	M3: 8,500→40	M3: W→RD
SC 4-4	M3: USA	M3: 4,500→18,000→40	M3: RL→W→RD
SC 5	M9: ASIA3	M9: 8,500→40	M9: W→RD
SC 6-1	M14: ASIA1	M14: 11,000→40	M14: W→RD
SC 6-2	M14: USA	M14: 4,500→18,000→40	M14: RL→W→RD
Supply chain scenarios for demonstrating the supplier options			
SC 7	M3, M4, M8, M9, and M14: ASIA1	All hot spots: 11,000→40	All hot spots: W→RD
SC 8	M3, M4, M8, M9, and M14: USA	All hot spots: 4,500→18,000→40	All: RD→W→RD

SC Supply chain scenario, *SS* stainless steel scenario, *M* raw material, *AU* Australia, *ASIA1 to ASIA3* three Asian countries, *USA* the United States of America, → next distance of the corresponding transportation, *RD* road transportation, *W* water transportation, *RL* rail transportation

SC8 were formulated as specified in Table 2 (white section). The first three scenarios, SC1 to SC3 aimed to change transportation type (e.g. road (RD) to rail (RL) or water (W)) and travel distances in km of the hot spots, M3, M4 and M8. These changes were expected to reduce environmental impact as rail transportation consumes less fuel and it also has a cheaper freight rate than road transportation. The shorter travel distance of the road transportation also consumes less fuel.

M3 is the main contributed raw material of environmental footprint and economic impact; therefore, SC4-1 to SC4-4 scenarios were developed to improve their impacts by varying the current locations of the four suppliers. These suppliers located in four alternative countries that offered different prices and utilised electricity generated from different combinations of energy sources (Ibbotson and Kara 2013). These countries include Australia (AU), three Asian countries (ASIA 1 to ASIA3) and the United States of America (USA). Their market prices have a standard deviation of 1.4 AU$(2011) and the coefficient of variation of 34 %.

SC5 was created for the next hot spot, M9 by focusing mainly on reducing its environmental footprint. It changed supplier from ASIA1 to ASIA3 in order to reduce the utilisation of road transportation and electricity sources that emit less GHG emissions. The standard deviation of these prices are 1.1 AU$(2011) and the coefficient of variation of 59 %. SC6-1 and SC6-2 tested the influences of two available suppliers towards M14 which have the standard deviation of the prices as 0.29 AU$(2011) and the coefficient of variation of 21 %.

Lastly, SC7 and SC8 aimed to improve all hot spots by changing the options of sourcing all raw materials from current suppliers to alternative suppliers from one regional location. SC7 represents a cost-efficient supplier from ASIA1 where the material costs are relatively lower than others but it requires water transportation for a longer travel distance. The standard deviation of the prices for this scenario is 1.82 AU$(2011) and the coefficient of variation of 65 %. SC8 is a supplier that can offer high quality raw materials from USA using road and water transportation for the longest travel distances. The standard deviation of their prices are 1.96 AU$(2011) and the coefficient of variation of 62 %.

3 Results and discussion

This section show the hotspot analysis results which were used to develop the 12 supply chain scenarios of 6,098 m GRP I-beams. Subsequently, the environmental footprint and the economic impact results of the current and the 12 supply chain scenarios of GRP I-beams with the stainless steel (316) I-beams (SS) scenario (see Tables 1 and 2) are compared. Most of the results in this research are presented in a percentage contribution due to the confidentiality agreement with the company. These results are considerably useful for manufacturers as an approach to support their decision making process of their production for future improvements by identifying ecological and economic hot spots, developing and assessing improvement scenarios.

3.1 Hot spot analysis

The hot spots of the impacts are identified by observing from the following values of the assessments in Figs. 1 and 2.

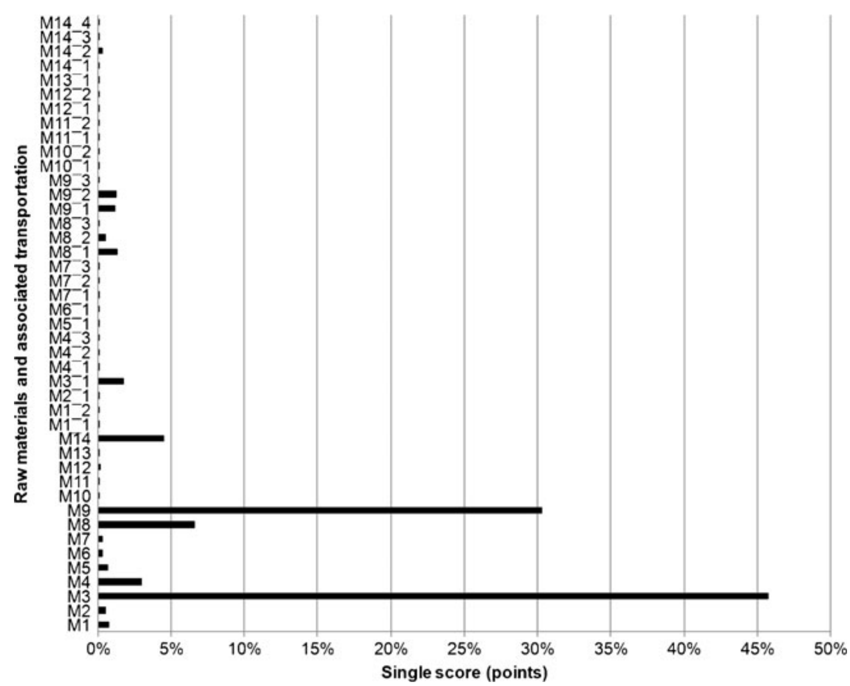


Fig. 1 Total environmental footprint in terms of the single score (*points*) for the raw materials and the associated transportation at the material stage of 6,098 m composite I-beams. Note: Raw material (*M*); the number of transportation involved in transferring the raw materials (M_1 to M_4)

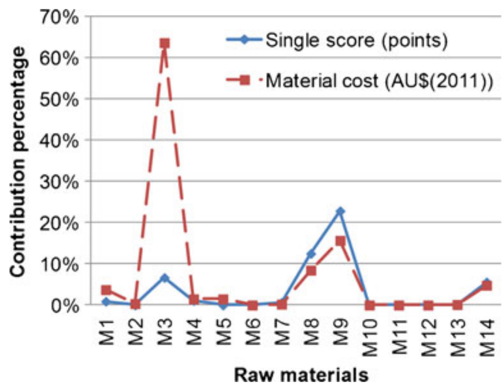


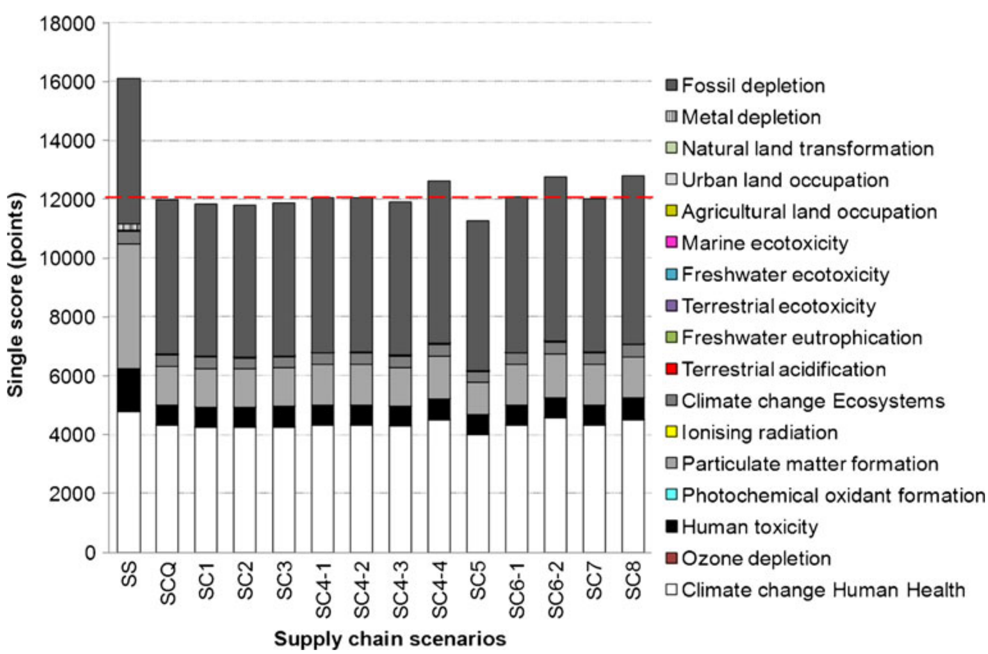
Fig. 2 Total environmental footprint in a single score (*points*) and the material costs of the raw materials (AU$(2011) which include the values of their associated transportation for making 6,098 m composite I-beams. Note: Raw material (*M*)

Figure 1 presents a contribution percentage of the single score value of the material stage for the GRP I-beams produced by the World ReCiPe endpoint method. It elaborates the distribution for the 14 raw materials (M1 to M14). These materials include fibre and plastic resins (M3–M5 and M8–M9) as well as specific chemicals (M1–M2, M6–M7 and M10–M14) such as additives and colour pigment. Their associated transportation of those raw materials is also presented (e.g. M1_1 and M1_2 are the first and the second mode of transportation used by M1). The transportation is used to deliver the raw materials from suppliers to the manufacturing plant. The ecological hot spots are observed in Fig. 1 as raw material M3, M9, M8, M14 and M4 where the top two hot spots (M3 and M9) contribute up to 45 % and 30 % to the total result. This is mainly due to the combinations of material weights and types, amount of consumed electricity and types of energy sources used to generate the electricity by different countries. For example, the plastic resins and glass fibre are used relatively higher quantities and consume higher electricity than other ingredients such as additives. The raw materials that produced from AU and ASIA 1 use electricity that are generated mainly from coal therefore, their environmental footprint would be larger than produced in other countries due to the higher GHG emissions.

To identify both ecological and economic hot spots, Fig. 2 presents the total impacts that caused by the raw materials and their associated transportation. The single score in this figure is the sum of the raw materials and their associated transportation obtained from Fig. 1. For example, 23 % of M9 in Fig. 2 is the contribution percentage of the summation of M9, M9_1 to M9_3 to the total single score values in Fig. 1. The material costs are the summation of the market prices of the raw materials and their associated transportation costs. The latter costs are the multiplication of the associated carriage weights, travel distances and freight rates.

According to Fig. 2, the hot spots for the ecological and economic impacts amongst the 14 raw materials are M3, M4, M8, M9 and M14. Both results are similarly fluctuated across the raw materials predominantly due to material types and weights. The market prices of the raw materials are contributed by up to 90 % of the total material costs in Fig. 2. The remaining 10 % causes by the associated transportation which influences mainly by the variation of carriage weights, combinations of transportation types, supplier locations and travel distances. The transportation costs distribute 2 % across the transportation, M3_1, M8_1, M9_2, M9_1, M8_2 and M14_2. This is due to the higher freight payment is applied when transporting heavy goods for longer travel distances via road and water transportation.

Fig. 3 The single score results and impact categories for the 6,098 m I-beams and the 12 supply chain scenarios obtained from the World ReCipe endpoint method. *SS* stainless steel, *SCQ* status quo scenario, *SC1 to SC8* scenario 1 to 8; *red dashed line* SCQ value



3.2 Environmental footprint results

The single score results of the 12 supply chain scenarios (SC1 to SC8) in Fig. 3 are less than the stainless steel I-beam (SS). Some of the scenarios give considerably lower values than that of the current GRP I-beam by 0.3 % to 11.2 %. These scenarios are SC1 (1.2 %), SC2 (0.3 %), SC4-3 (1.4 %) and SC5 (11.2 %). SC1 to SC3 have the least variation to SCQ as they demonstrate a simple change in supply chain configuration by shortening distances and selecting alternative types of transportation. The higher reduction (SC5) is mainly caused by using less road transportation which consume less fuel and also partly contributed by different supplier locations that use electricity generated from the lower environmental footprint energy sources. For example, the electricity generates from hydropower has significantly less environmental footprint than generated from coal.

Figure 3 also shows the breakdown of single score values into 17 impact categories where most of them are significantly less than SS across the 12 scenarios. The exception is found in the climate change, ozone depletion, photochemical oxidant formation, terrestrial acidification, natural land transformation and fossil depletion impact categories. They are also the similar drawback found in part 1 (Ibbotson and Kara 2013) as described in section 1. The ozone depletion and fossil depletion impact categories remain noticeably higher than SS. This is owing to the fact that the reductions of 1) methane and ethane emissions as well as 2) natural gas, oil and coal consumptions across the 12 scenarios are less than the SS which is currently 25 % and 7 % less than SCQ respectively.

Improvements for the remaining drawback impact categories are highlighted in Fig. 4 which obtained the characteristic results from the World ReCiPe midpoint method. These results are presented as they are less aggregated than the single score values which produced by the World ReCiPe endpoint method which provide higher uncertainties results (Recipe 2011). Main improvements are found in SC1 to SC3 and SC5 in Fig. 4 where their values are now less than SS and SCQ in all four impact categories. The root cause is due to road transportation consumes less fuel when transporting carrying heavy goods in a shorter travel distance or using rail instead. This benefit is particularly applied to the climate change impact category where approximately 85 % of the results are contributed by the amount of CO_2 emissions when observed from the LCI results. SC5 is further improved its environmental footprint values by using ASIA3 supplier for M9 in lieu AU in order to emit less GHG emissions as ASIA3 uses less coal-based electricity.

SC4-3 is improved in most of the impact categories except for the terrestrial acidification impact category. This is because even though by changing suppliers of M3 from AU to ASIA3, electricity decreases sulphur dioxide (SO_2) emission but higher SO_2 and ammonia (NH_3) are emitted from using water transportation for a longer travel distance. Other scenarios produce higher values in all impact categories due to two main reasons. They are higher emissions are generated from either different electricity generations from the alternative supplier locations (SC4-1 and SC6-1) or the longer travel distances of road and water transports (SC4-2 and SC4-4) or both reasons (SC5, SC6-2, SC7 and SC8).

3.3 Economic impact results

The economic impact results compare the direct raw material and transportation costs for the current cradle-to-gate of 6,098 m GRP I-beams, SCQ with SC1 to SC8 supply chains

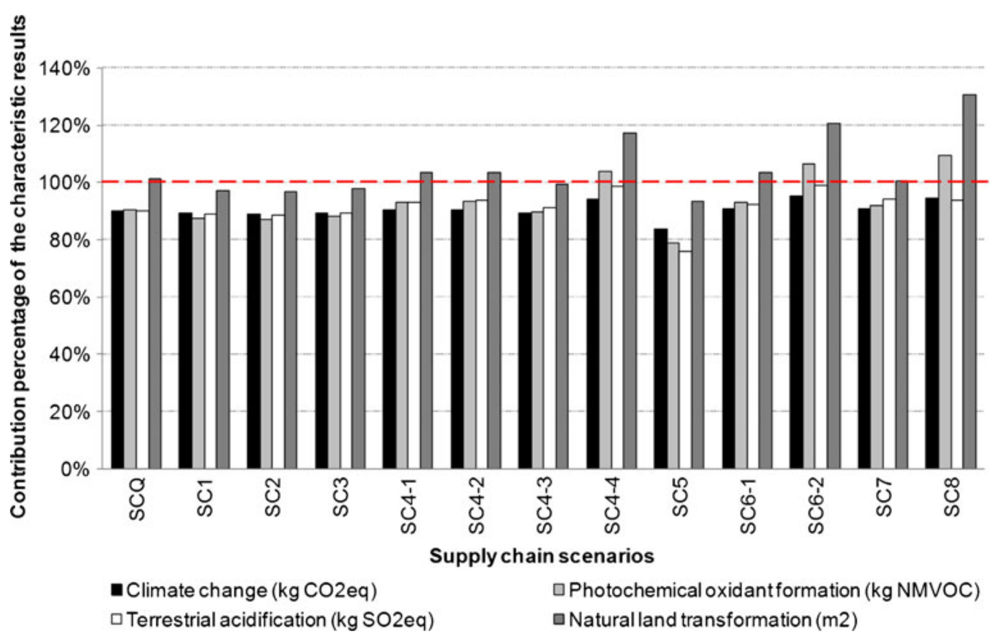


Fig. 4 Contribution percentage of the four characteristic results (obtained from the World ReCiPe midpoint method) for the 6,098 m I-beams and the 12 supply chain scenarios based on their associated stainless steel results (*the red dashed line*). *SCQ* status quo scenario, *SC1 to SC8* scenario 1 to 8

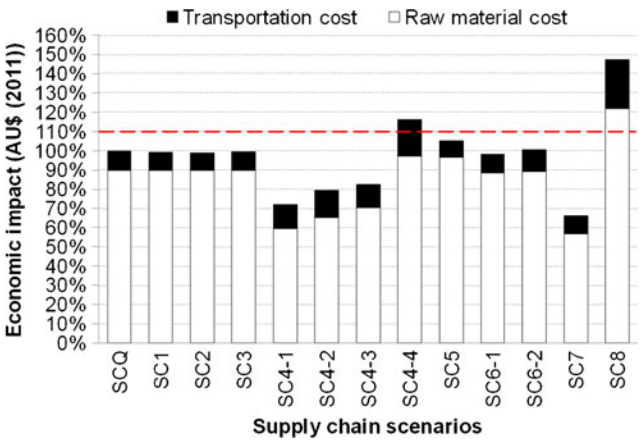


Fig. 5 Raw material and transportation costs in $AU(2011) for the cradle-to-gate of the 6,098 m I-beams based the status quo scenario. *SCQ* status quo scenario, *SC1 to SC8* scenario 1 to 8; *red dashed line* stainless steel value

scenarios as given in Fig. 5. These costs are generally varied amongst SC1 to SC8. Most of the supply chain scenarios have improved their economic performances. SC1 to SC3 and SC6-1 perform slightly better than SCQ when they avoid using the higher transportation freight rate such as road transportation or reducing travel distances.

SC4-1 to SC4-3 and SC7 in Fig. 5 reduce their economic impact significantly by 18 % to 34 % when sourcing their raw materials from cost effective suppliers. This reduction is obtained when replacing AU supplier of M3 to the three alternative suppliers for SC4-1 to SC4-3. The alternative prices have the standard variation of 1.13 AU$(2011) and the coefficient of variation of 38 %. On the contrary, SC4-4, SC5, SC6-2 and SC8 perform worse than SCQ. Their economic impact largely cause by the increased road transportation cost when they switch to the American supplier, except for SC5 where the increased raw material cost is compensated by the reduction of the transportation cost due to shorter travel distances.

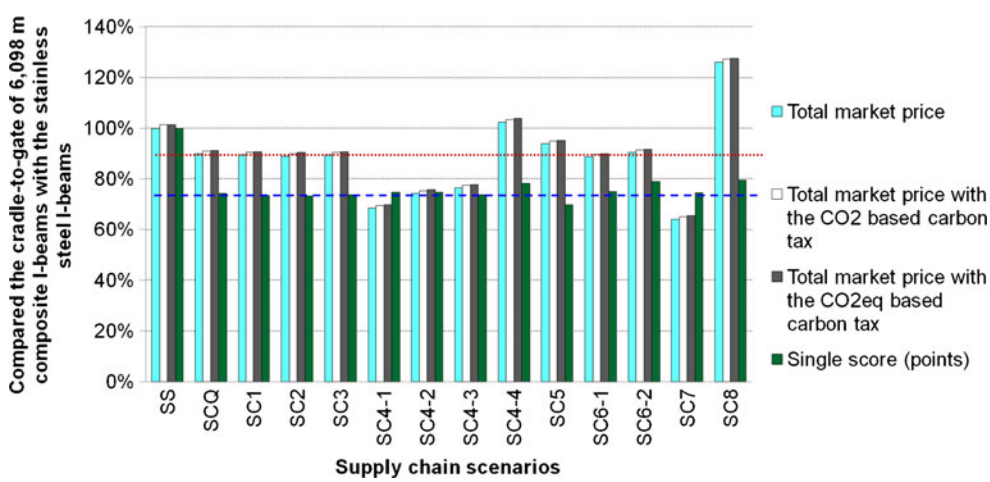
The red dashed line indicates the level of the stainless steel I-beams that assumed to be 10 % higher than SCQ's total market price. On this occasion, all supply chain scenarios of GRP I-beams have less economic impact than that of the stainless steel I-beams except SC4-4 and SC8. These two scenarios reflect a situation where a new supplier is introduced due to its advanced quality. However, the raw materials are available at a higher price with a higher delivery cost due to the longer travel distances of both road and water transportation.

Figure 6 presents the total market price results that combine all cost factors including the two potential carbon tax situations for the cradle-to-gate of the stainless steel. The current GRP and the 12 scenarios can be estimated by multiply the carbon tax of 23 AU$ per tCO_2 with the amount of 1) CO_2 emissions and 2) the GHG emissions which obtained from Fig. 4. The first situation demonstrates the common carbon tax situation where manufacturers require paying the tax for the amount of CO_2 emission that they emitted for their cradle-to-gate. The second situation is a possible future government policy that can potentially satisfy the Kyoto protocol (United Nations 1998) by considering the potential carbon tax based on GHG emissions (kg CO_{2eq}) for the cradle-to-gate of the I-beam scenarios.

These results in Fig. 6 are presented in the contribution percentage based on the total market prices of the current stainless steel I-beam and also compared with the single score results as previously reported in Fig. 3. Overall, the potential carbon tax values in Fig. 6 have slightly increased the total market prices of the I-beams which may seem to be insignificant. However, these values represent only for small production volume, if the volume is increased the manufacturers can gain benefits from minimising their carbon tax values. These benefits can be further highlighted by estimating the amount of the potential carbon tax under the two situations.

For the CO_2 based carbon tax situation, all scenarios of GRP I-beams would pay 25 % to 30 % carbon tax less than the

Fig. 6 A comparison of the contribution percentage for the environmental footprint (single score) and the three economic impact results (total market price) for the cradle-to-gate of the 6,098 m composite I-beams based on their associated results of the current stainless steel I-beams. *SS* stainless steel, *SCQ* status quo scenario, *SC1 to SC8* scenario 1 to 8



stainless steel I-beam. Amongst GRP I-beam scenarios, SC4-4, SC6-2 and SC8 would pay higher potential carbon tax than SCQ by approximate 5 %, and the opposite is true for SC5. These results are particularly revealing the significant impact towards the heavy vehicle utilisation which will be part of the Australian carbon tax in the future. For the CO_{2eq} based carbon tax situation, all GRP I-beam scenarios would intrinsically pay 10 % to 17 % potential carbon tax less than the stainless steel I-beams. Likewise, most alternative supply chain scenarios pay less potential carbon tax than SCQ by approximately 1 % to 7 %. This is owing to they use less fuel or sourcing suppliers that utilise electricity generated from low GHG emissions energy sources such as solar energy, hydro power and nuclear power. SC4-1, SC4-2 and SC4-4 pay 0.5 % to 5 % higher than SCQ due to GHG emitted from the fuel consumed by the trucks that carry heavy goods for longer travel distance.

When comparing the total market prices results from the current and the two carbon tax situations with the single score results (see Fig. 6), SC4-3 can be considered as the most promising scenario. This is because both environmental footprint and economic impact of this scenario are vastly improved. SC4-3 is influenced by much lower raw material cost from an alternative supplier which also requires less fuel and less emission substances during shipping the raw material. On the same token, SC1 to SC3 have also decreased both ecological and economic impacts by simply either reducing the travel distances or changing to less fuel consumption transportation. Under these scenarios, the manufacturers may select them to not only reduce their production cost but also to promote their green image based on the reduction of environmental footprint of their products.

On a contrary, SC4-4, SC6-2 and SC8 show the worse off situation as both impacts are increased owing to the higher raw material and delivery costs as well as longer travel distances for both road and water transportation. This situation may occur when there are limitations of the availability of the suppliers such as they provide high quality goods and bound by contract agreements within the stakeholders. The manufacturers may change their focus from these scenarios to other activities to improve both impacts such as increasing energy efficiency of the manufacturing processes.

The trade-off situations are also found in SC5 and SC6-1 where they attempted to improve one of the (ecological or economic) impacts and the other is equally worse off. The benefits gained from reducing the environmental footprint and the potential carbon tax of the new supplier in SC5 is outweighed an increased material cost. The economic impact of SC6-1 is improved when purchasing from cost effective supplier but the environmental footprint is increased due to the higher GHG emissions from electricity used by the alternative supplier. Under these circumstances, the manufacturers may hesitate to pursue the scenario particularly the businesses in the cost competitive market environment.

Lastly, the market prices of SC4-1, SC4-2 and SC7 illustrate the cost effective scenarios. They significantly reduce their economic impact by up to 16 % to 27 % by trade-off with a slightly increased environmental footprint (less than 1 %) and potential carbon tax values which caused by the electricity generated of the alternative suppliers. These scenarios can be a feel good motivation for the manufacturers where the suppliers are selected strategically to induce the cost saving without compromising the environmental performance of their products.

Thus far, these situations and scenarios were assessed under the system boundary of the cradle-to-gate. If the manufacturers are encouraged to extend their responsibility for an entire product life cycle (the cradle-to-grave) by their stakeholders or other environmental laws, the potential carbon tax of these two alternative I-beams would be different. This is because the benefits of the steel recovery from the recycling process of the stainless steel I-beam will be included. On this occasion, the potential carbon tax of the stainless steel becomes equal to SCQ whereby SC4-1, SC4-2, SC4-4, SC6-2 and SC8 are slightly higher than those two current GRP and stainless steel I-beams. SC5 and SC6-1 remain less than the two current I-beams as the benefit gained from reduction of both travel distances of the road and water transportation, is relatively higher than the benefit gained from the recycling process of the stainless steel I-beam.

4 Uncertainties and limitations

There are certain limitations and uncertainties in the environmental footprint and the economic impact assessments. In this section, only the limitations of the latter assessment are discussed in details where the former assessment is briefly summarised as the full discussion had already provided in part 1 (Ibbotson and Kara 2013).

Uncertainties were quantitatively analysed for the environmental footprint in four main assumptions. A breakeven analysis shown that the cradle-to-grave of GRP I-beam can be equalled to stainless steel I-beam if its environmental impact of the material stage that caused by using different process cases of chemicals is increased by up to 39 %. A sensitivity analysis was conducted for the estimation of the electricity consumption during the manufacturing process which was based on the worst scenario using electricity bills, nominal power consumption and operating hours. Results show that 6 % of the cradle-to-grave of GRP I-beam can be reduced when the estimated electricity is varied from current assumption (100 %) to 10 %. Minor variations of the modified electricity mix processes for the unavailable process cases were found when varying the percentage of energy resource

combinations in 2008 and 2009. The recycling rate of stainless steel was tested by changing from 70 % recycling and 30 % incineration to 100 % recycling. The single score results shown that the stainless steel I-beam will be increased by 2 %.

The economic impact for the cradle-to-gate of the I-beams was estimated based on several assumptions such as the exchange rates, Australian CPI values, the percentages of Australian production and overhead costs, Australian freight rates and carbon tax values. These assumptions were used to calculate the production and transportation costs as well as the total market prices for the composite and the stainless steel I-beams.

For this research, the production cost was estimated by summing 75 % of raw material, 9 % of transportation and 16 % of overhead which considers electricity, labour, machine and administration costs. The raw material costs were based on the advertised market prices which are limited for the associated raw material types and supplier locations. Therefore in practice, these prices may reduce further as a result of the negotiation during the purchasing process. Subsequently, the total market price of GRP I-beam was estimated by adding 50 % of the profit and tax margin to the estimated production cost. This profit and tax margin for the pultrusion profile may change significantly as it depends on the market and the set target of the manufacturers. Lastly, the stainless steel price was then assumed as 10 % higher than the total market price of GRP I-beam. The price of the hot rolled stainless steel (316) I-beam can also alter depending largely on supplier locations.

A sensitivity analysis was conducted to test the break-even of these assumptions before the total market price of GRP I-beam is higher than the stainless steel I-beam. As a result, the break-even points of the three key assumptions were found as follows. The raw material costs of M3, M4, M8, M9 and M14 may increase up to 13 %, the profit and tax margin can be increased up to 55 % and the total market price per kg of the stainless steel can be less than that of GRP I-beam by up to 16 %. These results revealed that the current analysis is in the range of the values found in literatures (Alibaba.com 2013; Bakis et al. 2002; Daniel 2003; Marsh 2000; Patrawala 1999; Plsek and Stepanek 2010; PULTRUSIONS.org 2012; Risbey et al. 2008; Starr 2000; United Business Media 2012; Tuakta 2004; Goel 2000; Orozco 1999; Wittcoff et al. 2012). To reduce these uncertainties and the limitations, more cost factors should be included in future analysis such as the negotiated price and insurance cost that depending on different transportation types and supplier locations.

5 Conclusions and recommendation

Part 2 of this research is the continuation of part 1 publication which revealed that the environmental footprint of GRP I-beam is less than the stainless steel I-beam in terms of the single score results. There were some shortcomings for certain impact categories including the climate change (Ibbotson and Kara 2013). Therefore, part 2 analysed the environmental footprint and the economic impact for the cradle-to-gate of the 6,098 m GRP and stainless steel I-beams. The hot spots for both ecological and economic impacts were identified and used to formulate 12 supply chain scenarios. The environmental footprint results were calculated in terms of LCI, characteristic and single score results which produced by the World ReCiPe midpoint and endpoint methods. The CO_2 and CO_{2eq} results from LCI were used to estimate the potential carbon tax for the economic impact. The uncertainties and limitation of the assessment were also tested by the sensitivity analysis. The break-event points of the three dominant assumptions shown that the outcome of this research will remain the same even if: the raw material costs of GRP I-beam are increased by up to 13 %, the profit and tax margin is less than 55 % and the stainless steel price per kg is 16 % less than GRP I-beam price.

Results in most supply chain scenarios of GRP I-beams have also less environmental footprint than that of the stainless steel I-beam. The economic impact results revealed that the raw material cost is practically the dominant cost factor when compared to the transportation cost. Different production strategies for manufacturers were discussed when comparing the benefit gained from both environmental footprint and economic impacts. The results showed that SC4-3 was found as the most win-win scenario as it has a potential to significantly reduce environmental footprint while increasing the competitiveness of the manufacturers. This is because SC4-3 sourced from the alternative supplier which reduces both fuel consumption from shorter travel distances of the road transportation and lower raw material prices. There are also the worse off and the trade-off scenarios where manufacturers have to make the decision of their action by considering other factors such as the availability of suppliers, the contract agreement, company image and the competitiveness in the market. If the proposed supply chain scenarios are not feasible, manufacturers may change their focus to other activities within their manufacturing system such as improving the energy efficiency of the manufacturing processes.

As it can be observed in the research, the environmental footprint and the economic impact were assessed under the scope of the cradle-to-gate. If the cradle-to-grave is considered, the advantage of the steel recycling process will equated the potential carbon tax values of current stainless steel, GRP I-beams and certain supply chain scenarios. Therefore, the mechanism in calculating the carbon tax should be extended to the entire life cycle stage to avoid the problem shift phenomenon. Future work can be further enhanced by including detailed cost elements such as insurance cost and discounted price that vary across different transportation types and supplier locations. Other manufacturing factors such as delivery

time may also be included in the assessment to further satisfy the manufacturing system in practice.

Acknowledgments The authors are grateful for the input data provided as part of the Composites: Calculating their Embodied Energy study funded by the Queensland Government through the Department of Employment, Economic Development and Innovation and, the participant composites companies and institutes.

References

Agrawal B, Tiwari GN (2010) Life cycle cost assessment of building integrated photovoltaic thermal (BIPVT) systems. Energy Buildings 42(9):1472–1481

Alibaba.com (2013) http://www.alibaba.com/ Accessed 13 February 2013

Ashby MF (2009) Materials and the environment: eco-informed material choice. Butterworth-Heinemann, London

Australian Government (2013) Carbon price. Clean energy future http://www.cleanenergyfuture.gov.au/clean-energy-future/carbon-price/#content01 Accessed 13 February 2013

Bakis CE et al (2002) Fiber-reinforced polymer composites for construction—state-of-the-art review. J Compos Constr 6(2):73–87

Bureau of Labor Statistics (2011) International Comparisons of Hourly Compensation Costs in Manufacturing, 2010. New release, US Department of Labor

Castella PS, Blanc I, Gomez Ferrer M, Ecabert B, Wakeman M, Manson J-A, Emery D, Han S-H, Hong J, Jolliet O (2009) Integrating life cycle costs and environmental impacts of composite rail car-bodies for a Korean train. Int J Life Cycle Assess 14(5):429–442

Daniel RA (2003) Environmental considerations to structural material selection for a bridge. European Bridge Engineering Conference-Lightweight Bridge Decks, Rotterdam

Dlamini N, Fujimura K, Yamasue E, Okumura H, Ishihara K (2011) The environmental LCA of steel vs HDPE car fuel tanks with varied pollution control. Int J Life Cycle Assess 16(5):410–419

Dobon A, Cordero P, Kreft F, Østergaard S, Antvorskov H, Robertsson M, Smolander M, Hortal M (2011) The sustainability of communicative packaging concepts in the food supply chain. A case study: part 2. Life cycle costing and sustainability assessment. In J Life Cycle Assess 16(6):537–547

Ecoinvent Centre (2010) The life cycle inventory data version 2.2. Swiss Center for Life Cycle Inventories

Goedkoop M, Heijungs R, Huijbregts M, Schryver AD, Struijs J, Van Zelm R (2009) ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, The Hague. VROM, The Netherlands

Goel A (2000) Economics of composite material manufacturing equipment. Bachelor of Science in Mechanical Engineering Dissertation, Massachusetts Institute of Technology, the United States of America

Helm D (2005) Economic instruments and environmental policy. Economic and Soc Rev 36(3):205–228

Hochschorner E, Noring M (2011) Practitioners' use of life cycle costing with environmental costs—a Swedish study. Int J Life Cycle Assess 16(9):897–902

Hong T, Han S, Lee S (2007) Simulation-based determination of optimal life-cycle cost for FRP bridge deck panels. Automat Constr 16(2):140–152

Ibbotson S, Kara S (2013) LCA case study. Part 1: cradle-to-grave environmental footprint analysis of composites and stainless steel I-beams. Int J Life Cycle Assess 18:208–217

International Energy Agency (2008) Electricity/Heat in 2008. www.iea.org/stats/electricitydata.asp?COUNTRY_CODE030. Accessed 17 October 2011

International Energy Agency (2009) Electricity/Heat in 2009. www.iea.org/stats/electricitydata.asp?COUNTRY_CODE030. Accessed 27 March 2012

International Energy Agency (2010) CO2 emissions from fuel combustion highlights, 2010th edn. IEA, Paris

International Energy Agency (2011) CO2 emissions from fuel combustion highlights, 2011th edn. IEA, Paris

James K (2003) Environmental life cycle costs in the Australian food packaging supply chain. Int J Life Cycle Assess 8(4):243–243

Kara S, Manmek S (2010) Composites: calculating their embodied energy report. Life Cycle Engineering and Management Research Group @ UNSW, Department of Employment, Economic Development and Innovation

Kara S, Manmek S, Kaebernick H (2007) An integrated methodology to estimate the external environmental costs of products. CIRP Ann-Manuf Techn 56(1):9–12

Kara S, Manmek S, Herrmann C (2010) Global manufacturing & the embodied energy of products. CIRP Ann - Manuf Techn 59:29–32

Kicherer A, Schaltegger S, Tschochohei H, Pozo B (2007) Eco-efficiency. Int J Life Cycle Assess 12(7):537–543

Laurent A, Olsen SI, Hauschild MZ (2010) Carbon footprint as environmental performance indicator for the manufacturing industry. CIRP Ann-Manuf Techn 59(1):37–40

Lee K-M, Cho H-N, Cha C-J (2006) Life-cycle cost-effective optimum design of steel bridges considering environmental stressors. Eng Struct 28(9):1252–1265

Lévová T, Hauschild MZ (2011) Assessing the impacts of industrial water use in life cycle assessment. CIRP Ann-Manuf Techn 60(1):29–32

Marsh E (2000) Composites in infrastructure-building new markets. Elsevier Science Ltd, Great Britain

Metz B, Davidson O, Bosch P, Dave R, Meyer L (2007) Climate change 2007: working group III: mitigation of climate change. IPCC Fourth Assessment Report: Climate Change 2007. The Intergovernmental Panel on Climate Change, http://www.ipcc.ch/publications_and_data/ar4/wg3/en/ch13s13-2-1-2.html

Orozco R (1999) Effects of toughened matrix resins on composite materials for wind turbine blades. Master of Science Dissertation, Montana State University-Bozeman

Patrawala TB (1999) Decision support tool for costing of the pultrusion process. Master of Science in Industrial & Management Systems Engineering Dissertation, West Virginia University, the United States of America

Plsek J, Stepanek P (2010) Optimisation of building structures I (DBSO). Eng Mech 17(5/6):307–321

PRe Consultants BV (2008) SimaPro 7 User's Manual. PRe Consultants BV, the Netherlands

PULTRUSIONS.org (2012) Advantages of using pultrusion. http://209.238.185.52/articles/advantages.html. Accessed 2 June 2012

Rainer W (2011) Employment and structural impacts of material efficiency strategies: results from five case studies. J Clean Prod 19(8):805–815

Rate Inflation (2011) Australia—consumer price index (CPI). www.rateinflation.com/consumer-price-index/australia-cpi.php. Accessed 2 June 2012

Recipe, Introduction (2011) http://sites.google.com/site/lciarecipe/project-definition. Accessed 22 February 2013

Risbey T, Cregan M, Mitchell D (2008) Freight rates in Australia 1964–65 to 2007–08. Information sheet 28. Department of Infrastructure, Transport, Regional Development and Local Government, Australian Government, Canberra

Schulz J, Kara S, Herrmann C, Manmek S, Dettmer T, Luger T (2011) Environmental footprint of single-use surgical instruments in comparison with multi-use surgical instruments. In: Herrmann JHC (ed)

18th CIRP International Conference on Life Cycle Engineering. Glocalized solutions for sustainability in manufacturing. Springer, Braunschweig, pp 623–628. doi:10.1007/978-3-642-19692-8_108
Song YS, Youn JR, Gutowski TG (2009) Life cycle energy analysis of fiber-reinforced composites. Compos Part A: Appl S 40(8):1257–1265. doi:10.1016/j.compositesa.2009.05.020
Starr TF (2000) Pultrusion for Engineers. Woodhead Publishing, Cambridge
Sumner J, Bird L, Smith H (2009) Carbon taxes: a review of experience and policy design considerations. National Renewable Energy Laboratory, the United States of America
Tae S, Shin S, Kim H, Ha S, Lee J, Han S, Rhee J (2011) Life cycle environmental loads and economic efficiencies of apartment buildings built with plaster board drywall. Renew Sust Energ Rev 15(8):4145–4155
Tsai W-H, Lin S-J, Liu J-Y, Lin W-R, Lee K-C (2011) Incorporating life cycle assessments into building project decision-making: an energy consumption and CO2 emission perspective. Energy 36(5):3022–3029
Tuakta C (2004) Use of fibre reinforced polymer composite in bridge structure. Master of Engineering in Civil and Environmental Engineering Dissertation, Massachsetts Institute of Technology, the United States of America
United Business Media (2012) www.prnewswire.com. Accessed 2 June 2012
United Nations (1998) Kyoto protocol to the United Nations framework convention on climate change
Witik RA, Payet J, Michaud V, Ludwig C, Månson J-AE (2011) Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Compos Part A: Appl S 42(11):1694–1709
Wittcoff HA, Reuben BG, Plotkin JS (2012) Industrial organic chemicals. Wiley, New Jersey
Woodard A (2011) LCA—the heart of future Australian building environmental regulations and specifications. Paper presented at the the ALCAS 7th Australian Conference on Life Cycle Assessment, Melbourne
X-RatesTM (2012) www.x-rates.com. Accessed 2 June 2012